On the complex stellar populations of ancient stellar systems

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6. Concluding remarks and future prospects

In this thesis I developed and validated tools to investigate the detailed properties of ancient stellar populations in the Local Group. In chapter 2 I have shown that current star formation history (SFH) analysis, based on the main sequence turn-off (MSTO), becomes less accurate at old ages. This was shown by analysing the horizontal branch (HB) of the Carina dSph, highlighting how star formation in certain regions of the age-metallicity space is ruled out by the absence of specific features in the observed HB of this galaxy. This demonstrated that the HB contains additional information that can be used to refine the accuracy of our measurements of the SFH of galaxies, based on their resolved populations.

This result motivated me to develop a new colour-magnitude diagram (CMD) modelling tool, presented in chapter 3, that, for the first time, determines the SFH of a galaxy combining detailed HB and MSTO modelling. The additional constraints coming from the HB result in a noticeable increase in the age resolution. This new approach also determines the amount of mass lost by stars on the RGB, providing precious insights to this long-standing uncertainty. This new method was demonstrated on the well studied Sculptor dwarf spheroidal galaxy (dSph), where the careful modelling of the HB can clearly distinguish the two known events of star formation. These two events are more accurately measured that previous SFH analysis allowed, based only on the MSTO.

An application of this method to the distant Tucana dSph, in chapter 4, further demonstrated that, with high quality photometry, the modelling of the whole CMD, including the HB, improves the accuracy of the early star formation history of resolved galaxies. I confirmed the presence of the two distinct stellar populations that were already known and reported the presence of an additional third, younger, stellar population. This new and more detailed SFH for Tucana clearly shows that a multimodal stellar distribution along the HB is directly linked to a similarly complex star formation history. Not of minor importance, the modelling of the whole CMD resulted in a very accurate measurement of the RGB mass loss.

The work I carried out on dSphs contributes to the study of complex ancient stellar populations in low mass galaxies. The presence of distinct stellar components in these galaxies has been established by many independent investigations. The origin of this complexity is still unclear. Some of the proposed scenarios invoke mergers of different stellar systems (Amorisco & Evans, 2012a; del Pino et al., 2015) or bursty in-situ star formation (Salvadori et al., 2008; Revaz et al., 2009), potentially providing constraints to the picture of hierarchical mass assembly and to the efficiency of supernova feedback in low mass haloes. To date, our observational characterisation of dSphs cannot provide a clear picture of the early history of these systems. With the possibility to accurately detect these distinct early stellar components in a SFH, we can add valuable information. Reliable time scales are notoriously challenging to obtain for old stellar populations.

The next logical step for the work presented in chapters 2, 3 and 4 will be to extend the analysis of the HB to additional Local Group dSphs, to build a large sample of accurate high-resolution SFHs. This will provide us with the ability to identify differences and similarities in the very early history of Local Group galaxies. In a broader context, the information of the detailed SFH of dSphs can be combined with the constraints coming from chemical abundance and velocity measurements, to build a complete picture of the chemo-dynamical mechanisms that shape low mass galaxies, with the aim of disentangling the relative contributions of environmental and internal processes.

A second, equally important, benefit of modelling a larger sample of dSphs with MORGOTH will be to obtain a large number of measurements of the RGB mass loss in different extragalactic stellar systems. Such measurements will make it possible to understand this poorly constrained process, which remains one of the biggest uncertainties in stellar evolution theory. In addition, being able to determine the behaviour of RGB mass loss in a range of stellar systems will make it possible to calibrate the process, enabling us to measure detailed SFHs from the bright CMD alone. Detailed SFH measurements have so far mostly been confined to the Local Group,

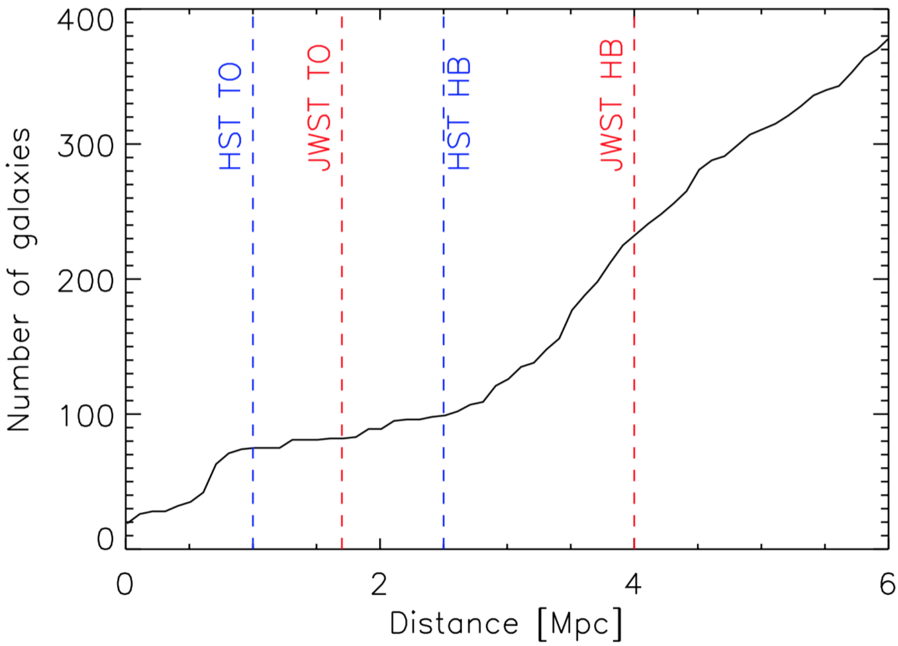

Figure 6.1: The cumulative number of known galaxies as a function of distance from the Milky Way, from the catalogue of Karachentsev et al. (2013). The dashed lines represent the detection limits, for 10 hours of integration, with HST and JWST of either old turn-off and horizontal branch stars in a 12.5 Gyr old stellar population with a metallicity of [Fe/H] = -2.0.

due to the necessity of detecting the old MSTOs. This not only limits the available sample of galaxies for which we have access to the old record of star formation, but also raises the possibility that the Local Group could somehow be a special environment, biasing our view of galaxy formation.

Next generation observing facilities, such as the James Webb Space Telescope and the 30-m class observatories, will provide increased sensitivity and spatial resolution that will allow us to resolve individual stars in more distant galaxies. Fig. 6.1 shows the cumulative distribution of known galaxies as a function of distance from the Milky Way. It can be seen how the improved observing capabilities of the James Webb Telescope will only slightly increase the number of galaxies that can be resolved down to MSTO. This is due to the inhomogeneous distribution of galaxies on scales of a Mpc. In contrast, HBs are much brighter than the equivalent MSTOs and will be detectable for galaxies many Mpc away.

Table 6.1: List of Galactic star clusters included in the Wide-Field Strömgren survey carried out in June 2018. Metallicities, half light radii (r_h, in arcminutes) and relaxation times at the half light radius (t_h, in years) come from the 2010 version of Harris (1996). Estimates for the mass come from Baumgardt (2017).

Name	Alternative Name	$[Fe/H]$	$\log \frac{M}{M_\odot}$	r_h	$\log t_h$
NGC 5024	M 53	-2.10	5.58	1.31	9.76
NGC 5634		-1.88	5.33	0.86	9.54
NGC 5904	M 5	-1.29	5.57	1.77	9.41
NGC 6093	M 80	-1.75	5.40	0.61	8.80
NGC 6171		-1.02	4.94	1.73	9.00
NGC 6218	M 12	-1.37	4.94	1.77	8.87
NGC 6229		-1.47	-	0.36	9.15
NGC 6254	M 10	-1.56	5.26	1.95	8.90
NGC 6341	M 92	-2.31	5.43	1.02	9.02
NGC 6535		-1.79	4.3	0.85	8.20
NGC 6712		-1.02	-	1.33	8.95
NGC 6791	M 107	0.41	-	-	-
NGC 6838	M 71	-0.78	4.69	1.67	8.43
NGC 7078	M 15	-2.37	5.66	1.00	9.32
NGC 7089	M 2	-1.65	5.76	1.06	9.40
Palomar 5		-1.41	-	2.73	9.82
Palomar 11		-0.40	-	1.46	9.34
Palomar 14	AvdB	-1.62	-	1.22	10.02

As demonstrated by Boylan-Kolchin et al. (2016), the study of nearby galaxies probes a co-moving volume that extends much beyond the present size of the Local Group neighbourhood. Thanks to the analysis of the HB with James Webb Space Telescope, we will have access to the formation histories for a sample of galaxies that is roughly five times larger than we have today. The co-moving volume spanned by the progenitors of these systems is expected to be of the order of $10^4 Mpc^3$ at $z \sim 7$, which is a cosmologically representative sample of the early Universe and much larger than what is probed by the HST Ultra Deep Field or any future deep JWST field.

Chapter 5 was devoted to the study of the massive globular cluster NGC6205 (M13). Carrying on on the work of Carretta et al. (2011) and Massari et al. (2016), I confirmed the effectiveness of Strömgren photometry to detect the multiple stellar populations in a resolved globular cluster. I analysed the spatial distribution of the multiple stellar populations out to 6.5 half-light radii and found no evidence for radial segregation in any region of the cluster. The comparison of my results with the work done on M3, which is similar to M13 in many regards and has a strong radial gradient in its multiple population distribution, not only highlights how these clusters are different in their multiple stellar population properties, but shows the importance of taking the dynamical state into account when characterising distinct components in dense stellar systems. In this regard, when complementary information on the stellar content comes from, e.g., the HB modelling, the distributions of multiple stellar population within a globular cluster can prove to be an independent clock for the dynamical evolutionary state of the object.

As for dSphs, the next step forward would be to carry a large survey of the multiple populations in globular clusters, employing Strömgren photometry to probe the outer regions of these systems. In June 2018 I have carried out wide-field Strömgren imaging, with the Wide-Field Camera on the Isaac Newton Telescope, for 17 globular clusters and one old open cluster (NGC6791), over a field of view of about 30×30 arcmin.

A list of the targets observed, along with some key properties, is reported in Table 6.1. Some of these targets have never been searched for multiple populations before (NGC 6229 and Palomar 11), whereas only tentative evidence exists for others (NGC 6791 and Palomar 14). The data reduction strategy and the analysis will be developed from the procedure outlined in chapter 5. The main goal of this survey will be to identify, if present, and trace the multiple populations out to the most external regions of the targets. Where sample overlap is present, this data will be a useful complement to HST surveys, which are deep and precise but have limited spatial coverage, and high-resolution spectroscopic investigations, which are limited by the sample size.